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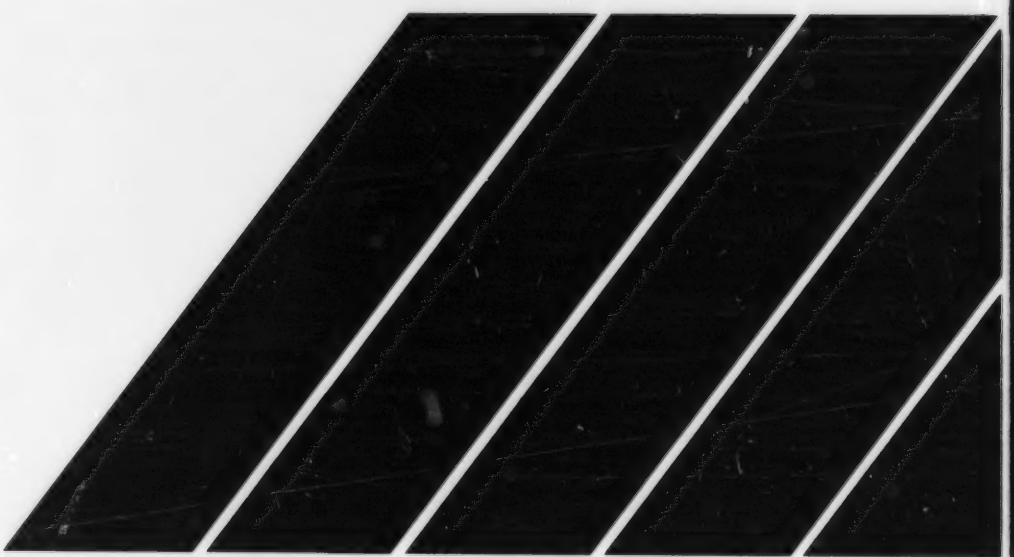
MIDNIGHT SUN



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MIDNIGHT SUN

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ABSTRACT

MIDNIGHT SUN—the University of Waterloo's solar-electric car—was designed and built by about 30 engineering, kinesiology and physics students for the GM SUNRAYCE USA held in July of 1990. The car measures 2 metres by 4.2 metres, weighs 224 kg (500 lbs), can collect about 1000 watts of solar electricity in full sun, and had a top speed during the GM SUNRAYCE USA of 79 km/hr (49 mph). The GM SUNRAYCE USA was an eleven day, 1644 mile road race from the Epcot Center in Lake Buena Vista, Florida to the GM Technical Center in Warren, Michigan. Thirty-two cars, powered only by solar energy, competed in this race.

MIDNIGHT SUN showed it's potential during the race qualifying runs by completing the required qualifying course with the 12^{th} fastest time of 52.83 seconds, and the 6^{th} fastest trap speed of 63 km/hr (39 mph). During the SUNRAYCE, MIDNIGHT SUN came in second on Day 1 of the race, tenth on Day 6, and eighth on Day 7, and was one of only 17 solar cars that were able to make it up the toughest hill in the race on Day 8.

MIDNIGHT SUN was in 17^{th} place overall at the end of Day 9. At about 11:00 am on Day 10 in Ohio, the Waterloo car was moving at 60 km/hr when it was bumped off the road by an out of control pickup truck. The solar car driver was not hurt. Despite the difficulties, the next day MIDNIGHT SUN was repaired and driven across the finish line at the ceremonial finish of the GM SUNRAYCE USA at the GM Technical Center in Warren. After receiving time penalties for not completing the last day and a half of the race, MIDNIGHT SUN was awarded 24^{th} place with an official cumulative time of 114 hours 37 minutes and 15 seconds.

MIDNIGHT SUN will be put on public display at the Ontario Science Centre in Toronto in January 1991, and will remain there for about three years.

RÉSUMÉ

MIDNIGHT SUN, la voiture solaire de l'Université de Waterloo, est la création de 30 étudiants en ingénierie, physique et cinésiologie dans le cadre de la SUNRAYCE USA, qui a eu lieu en juillet 1990. Le véhicule, qui mesure 2 mètres par 4,2 mètres et pèse 224 kg (500 lbs), est capable de collecter 1000 watts d'électricité d'origine solaire par temps de plein soleil et peut atteindre une vitesse de 79 km/heure (49 mph) démontrée lors de la course GM SUNRAYCE USA. Cette course, d'une durée de 11 jours, couvre une distance de 1644 miles de Epcot Centre au lac Buena Vista en Florida au Centre technique de GM à Warren au Michigan. Ont pris part à cette course, 32 véhicules, tous exclusivement propulsés à l'énergie solaire.

MIDNIGHT SUN, a démontré sa valeur au cours de l'épreuve de qualification en réalisant le 12^{e} meilleur temps soit de 52,83 secondes et le 6^{e} meilleure vitesse chronométrée soit de 63 km/heure (39 mph). Durant la course SUNRAYCE, MIDNIGHT SUN s'est placée 2^{e} le premier jour, 10^{e} le sixième jour, 8^{e} le septième jour et était l'une des 17 voitures capables de monter la pente la plus escarpée du parcours le huitième jour.

MIDNIGHT SUN était en 17^{e} place à la fin du neuvième jour. Vers 11 h, le dixième jour en Ohio, la voiture de l'Université de Waterloo progressait à 60 km/h lorsqu'elle a été frappée par une camionnette hors de contrôle. Le conducteur de la voiture solaire n'a pas été blessé. Après quelques réparations, MIDNIGHT SUN se retrouvait sur la route le lendemain et traversait la ligne d'arrivée. Pénalisée pour ne pas avoir accompli le dernier lapse du trajet dans le temps prescrit pour les raisons décrites, MIDNIGHT SUN s'est tout de même vu décerné un prix pour la 24^{e} place avec un temps cumulatif officiel de 114 heures 37 minutes et 15 secondes.

MIDNIGHT SUN sera exposée au Centre des sciences de l'Ontario à Toronto à partir de janvier 1991 pendant une période de trois ans.

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C "Design Considerations for a Solar Car PV Power System"

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PHOTO 1

The GM Sunrayce USA logo and a commemorative sidewalk brick were laid in a park in Greenville, Ohio.

PHOTO 2

MIDNIGHT SUN on display at the 1990 Expo of Wheels, Auto and Motorsport Show, October 19-21, 1990 in Toronto, Ont.

PHOTO 3

Team members examine the car after bringing it home from the race. From left to right, Shawn Marshall, Bradley Childs, Jordon Smith, Jonathon Lawrence, Karl Rueb, Rob Leslie, Craig McEwen, Mark Gagnon and Sheri Brown.

PHOTO 4

MIDNIGHT SUN is taken out for a final test drive around a University of Waterloo parking lot before being retired to the Ontario Science Centre in Toronto, Ont.

PHOTO 5

MIDNIGHT SUN beside a corn field in Ohio on US-127 after the accident on July 18, 1990.

Photo 1

Photo 2

Photo 3

Photo 4

Photo 5

Chapter 1

INTRODUCTION

MIDNIGHT SUN—the University of Waterloo's solar-electric car—was designed and built by about 30 engineering, kinesiology and physics students for the GM SUNRAYCE USA held in July of 1990. The car measures 2 metres by 4.2 metres, weighs 224 kg (500 lbs), can collect about 1000 watts of solar electricity in full sun, and had a top speed during the GM SUNRAYCE USA of 79 km/hr (49 mph).

The GM SUNRAYCE USA was an eleven day, 1644 mile road race from the Epcot Center in Lake Buena Vista, Florida to the GM Technical Center in Warren, Michigan. The race was organized by GM and its Chevrolet Motor Division, the U.S. Department of Energy and the Society of Automotive Engineers. Thirty-two cars, powered only by solar energy, competed in this race.

The purpose of this report is to provide an account of the Midnight Sun project to Energy Mines and Resources by giving an overview of the solar car's characteristics and performance during the race.

Chapter 2

MIDNIGHT SUN VEHICLE DESCRIPTION

The MIDNIGHT SUN vehicle was designed to take advantage of the competition rules to produce the maximum overall efficiency in a road-going vehicle. Although the majority of the 32 entries produced a vehicle at least broadly similar to the 1987 GM SUNRAYCER, Waterloo decided at the outset to use a different configuration in an effort to make incremental improvements in both aerodynamics and rolling resistance.

The overall vehicle was approximately 4.2 m long by 2.0 m wide: significantly shorter than the maximum allowable length of 6 m. This was achieved by positioning the driver directly under the 2 m by 4 m solar array, see Appendix A and Figure 1 in Appendix B. The driver's head protrudes from the array, but is completely covered, with either a windshield in front or solar cells behind, for optimum aerodynamics. Although some solar efficiency was sacrificed with this configuration, the vehicle was shorter, giving a lower overall weight and a smaller surface area for improved aerodynamics.

A three-wheeled configuration was adopted for simplicity and reduced weight. The two front wheels were steered and the single rear wheel was driven using a combination chain and timing belt drive directly from the motor. A single gear ratio was selected, although this gear ratio was changed mid-way through the race

by replacing one of the timing belt sprockets. This provided more torque to improve performance on the more hilly terrain encountered at this stage of the race. The vehicle was powered using a brushless DC electric motor designed specifically for lightweight electric vehicles. The motor and controller were purchased from UNIQ Mobility, Colorado, USA. Both performed flawlessly throughout the race. The motor, motor controller and the battery pack were mounted amidships, between the driver cockpit and the rear wheel, for improved weight balance. Details of the power system are outlined in a paper, reproduced as Appendix C.

All wheels used a simple spring suspension to reduce energy loss and improve driver comfort. No separate shock absorbers were used. Vehicle braking was achieved using disk brakes on the front wheels. These brakes were designed and built by the student team based on components from a snowmobile. The braking performance was improved dramatically when the metal pads supplied for the snowmobile were replaced with fiber pads fashioned from automotive components. In addition to these mechanical brakes, regenerative braking was provided through the rear wheel using the motor as a generator. The energy produced was returned to the batteries.

The three wheels were connected using a triangular aluminum subframe. All vehicle loads were shared by the aluminum subframe and the composite vehicle shell. The shell was constructed using a composite sandwich of Twaron-fabric-reinforced epoxy resin over a six mm thick Airex foam core. The driver was completely protected with a reinforced cockpit as well as an aluminum roll bar attached directly to the aluminum subframe. The driver was secured to the form-fitting seat using a five-point safety harness. This construction method produced a strong, safe vehicle. Although the vehicle was struck by a pickup truck and launched into a corn field on Day 10 of the race, no driver injuries occurred.

Small scale wind tunnel studies were performed to refine the aerodynamic shape of the vehicle. Direct comparisons with a similar model of the GM SUNRAYCER showed modest improvements in aerodynamic drag and stability. Specific attention was paid to both the top and bottom vehicle profiles to ensure that no positive lift was produced, under both direct and cross-wind conditions. The encouraging results of these studies were verified when the completed vehicle showed no aerodynamic instability in the presence of severe wind gusts. Ventilation for both the driver and the battery compartment was provided using two NACA ducts molded into the bottom of the shell.

Chapter 3

RACE PERFORMANCE

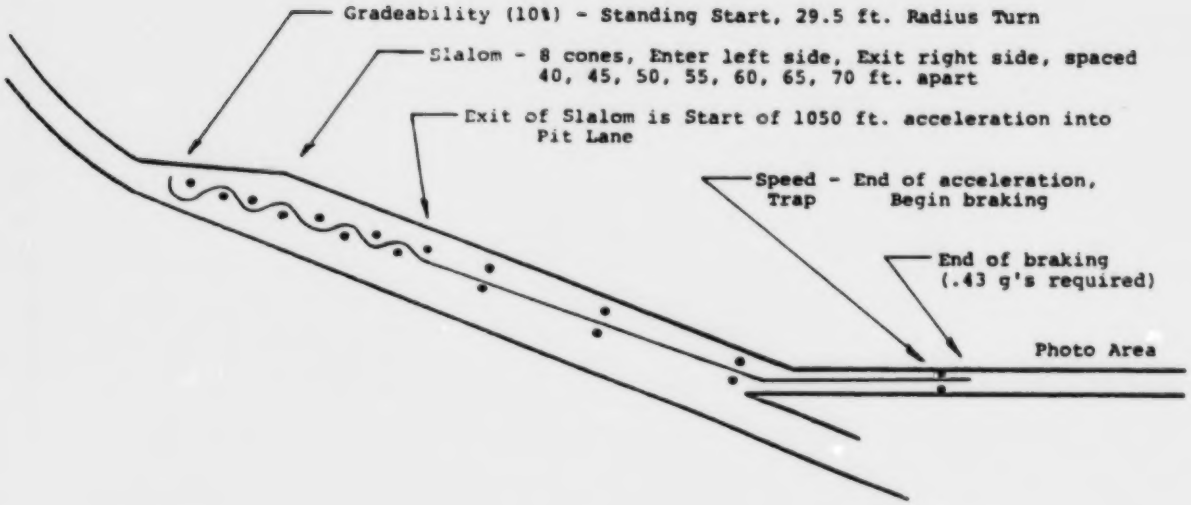
3.1 General Performance

MIDNIGHT SUN showed it's potential during the race qualifying runs by completing the required qualifying course with the 12^{th} fastest time of 52.83 seconds, and the 6^{th} fastest trap speed of 63 km/hr (39 mph). The qualifying course, which consisted of a gradeability test, a slalom run and an acceleration run, is shown in Figure 3.1. During the race, MIDNIGHT SUN was one of only 17 solar cars that were able to make it up the toughest hill in the race on Day 8.

MIDNIGHT SUN experienced both mechanical and electrical difficulties during the course of the race. The details of the most important of these are described in this chapter. Mechanical and electrical problems were a common occurrence for almost all of the 32 solar cars in the GM SUNRAYCE USA. In fact, the University of Michigan's car, Sunrunner, was the only car of the 32 entrants that covered the complete race route within regulation time every day of the race.

Despite the difficulties that MIDNIGHT SUN experienced, the car's performance was demonstrated to be competitive.

DAYTONA QUALIFYING COURSE


Gradeability (10%) - Standing Start, 29.5 ft. Radius Turn
Slalom - 8 cones, Enter left side, Exit right side, spaced 40, 45, 50, 55, 60, 65, 70 ft. apart
Exit of Slalom is Start of 1050 ft. acceleration into Pit Lane
Speed Trap - End of acceleration, Begin braking
End of braking (.43 g's required)
Photo Area

All Testing On Level Track Except Gradeability

SLALOM COURSE

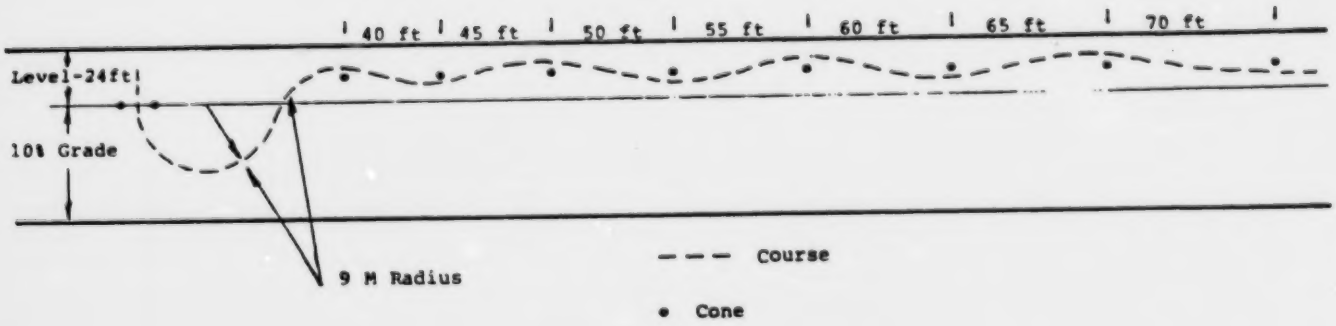


Figure 3.1: The GM SUNRAYCE USA qualifying course layout.

Table 3.1: Summary of MIDNIGHT SUN GM SUNRAYCE USA Results

Qualifying Position	— 13^{th} overall, with 6^{th} fastest trap speed of 63 km/h (39 mph).
Day 1	— **Second place Award** for the day.
Day 2	— 16^{th} for the day; 9^{th} overall. (Mechanical difficulties.)
Day 3	— 25^{th} for the day; 15^{th} overall. **Sportsmanship Award**
Day 4	— 31^{th} for the day; 21^{th} overall. (Electrical Problems)
Day 5	— 23^{th} for the day; 23^{th} overall. (Back on the road.)
Day 6	— 10^{th} for the day; 22^{th} overall. **"Most Improved" Award**
Day 7	— 8^{th} for the day; 15^{th} overall. (Moving up!)
Day 8	— 18^{th} for the day; 16^{th} overall. (Solar cell problems.)
Day 9	— 18^{th} for the day; 17^{th} overall. (Mechanical difficulties.)
Day 10	— 31^{th} for the day; 21^{th} overall. **Teamwork Award** (Bumped off the road at 11:00 am.)
Day 11	— 31^{th} for the day; 24^{th} overall. (No driving today.)

3.2 Race Statistics

A summary of the daily race performance results for the MIDNIGHT SUN car is presented in Table 3.1. A copy of the official cumulative race results is shown in Table 3.2. The fastest speed achieved by MIDNIGHT SUN during the race was 79 km/h (49 mph). The daily average speed of MIDNIGHT SUN (including the times taken for rest and maintenance stops) was 59 km/h (36 mph) for the 120 km traveled on Day 1, 20 km/h (13 mph) for the 186 km traveled on Day 6, and 35 km/h (21 mph) for the 199 km traveled on Day 7. Days 1 and 7 were the only two days that MIDNIGHT SUN traveled the complete official daily race distance in less than the official available race time of 9.5 hours.

Table 3.2

RAYCE STANDINGS

Day 11 Results In Order of Cumulative Times July-19-1990

	School Name	Team Name	Team No.	Daily Elapsed Time	Penalty Time	Official Elapsed Time	Cumulative Elapsed Time Hrs	Min	Sec
1	U. Michigan	Sunrunner	2	3:44:19		3:44:19	72:	50:	47
2	WWU	Viking XX	XX	2:46:43		2:46:43	74:	10:	06
3	Maryland	Pride of Maryland	1	3:15:26		3:15:26	80:	10:	55
4	Cal State L.A.	Solar Eagle	19	3:48:40		3:48:40	81:	03:	44
5	Crowder	Star II	33	3:33:24		3:33:24	81:	06:	18
6	MIT	Galaxy	5	4:02:14		4:02:14	83:	57:	37
7	Stanford	SUnSUrfer	100	4:18:02		4:18:02	93:	56:	53
8	WMU/Jordan	Sunseeker	77	3:15:51		3:15:51	96:	55:	20
9	CSU	Stelar V	61	4:03:17		4:03:17	97:	55:	06
10	Cal Poly Pomona	Solar Flair	25	4:58:21		4:58:21	99:	05:	57
11	Drexel	SunDragon	76	5:06:50		5:06:50	100:	03:	40
12	RIT	Spirit	10	4:48:45		4:48:45	104:	21:	18
13	Stark	Solis Tyrannus Cognoscis	22	4:02:03	1:12:30	5:14:33	105:	06:	47
14	WPI	Starduster	90	3:17:04		3:17:04	106:	34:	60
15	Auburn	Sol of Auburn	11	5:57:30		5:57:30	107:	24:	35
16	Mankato	Northern Light	3	4:19:32		4:19:32	108:	18:	45
17	Iowa St.	PrISUm	9	5:03:01		5:03:01	109:	08:	29
18	UNT	Centennial	8	4:46:58		4:46:58	110:	48:	04
19	Cal St. Northridge	CSUN-Blazer	0	4:52:35		4:52:35	110:	49:	57
20	Rose-Hulman	Solar Phantom	74	6:13:12		6:13:12	111:	07:	44
21	Cal Poly SLO	Sun Luis	101	4:36:39		4:36:39	113:	00:	15
22	U.T.	Texas Native Sun	36	4:44:52		4:44:52	113:	15:	25
23	Dartmouth	Sunvox III	96	4:23:57		4:23:57	113:	48:	13
24	Waterloo *	Midnight Sun	24	8:03:00		8:03:00	114:	37:	15
25	FIT	Sunshine Special	26	6:40:54		6:40:54	116:	39:	41
26	Penn	Solsation	250	8:07:00		8:07:00	122:	14:	48
27	Virginia Tech	VT SOLARAY	6	6:17:12		6:17:12	130:	27:	08
28	Clarkson	Kalahkwancha	4	6:44:48		6:44:48	131:	52:	00
29	Ottawa	Team Ralos	37	4:40:49		4:40:49	132:	48:	19
30	UPRM	The Shining Star	92	6:55:06		6:55:06	135:	44:	30
31	ASU	Sun Devil Cruiser	7	5:48:42		5:48:42	136:	49:	18
32	Villanova	Wild Solarcat	111	4:45:12		4:45:12	137:	04:	11

* Waterloo was running in 17th place when it was eliminated from competition by an out of control pickup truck

3.3 Problems and Solutions

3.3.1 Mechanical Problems

The one main mechanical problem with the MIDNIGHT SUN was the weakness of the single rear wheel suspension and drive linkage. Two factors contributing to the loads experienced by the rear suspension were (i) that the drive belt tension and the motor torque applied a bending moment to the rear of the frame where the rear suspension is attached, and (ii) that the single rear suspension had more "spring" in it than the front suspension, which caused the back of the car to be bounced up and down more than the front. The motor torque applied a pulling force on the timing belt that transferred power from the motor to an intermediate shaft mounted to the frame. This pulling force resulted in some flexure of the frame, which produced small misalignments in the drive train. The bouncing of the rear suspension put a heavy dynamic load on the rear suspension.

The combination of these effects resulted in a failure, on Day 2 of the race, of the rear wheel bearing. Later in the race, problems were experienced with the timing belt sprocket on the motor caused by excessive wear due to misalignment.

It should be noted that there was probably more wear and tear on the car's suspension while the car was being transported inside the trailer than when the car was on the road. This could have been avoided by supporting the car on blocks (of say, foam) while in the trailer, but then care would have to be taken to avoid damage to the car body which would then have had to take the inertial loads of the car weight.

In summary, the single rear drive wheel concept proved to be good in terms of vehicle handling and performance, but MIDNIGHT SUN would have benefited

from stronger rear suspension and suspension-to-frame attachment points.

3.3.2 Electrical Problems

The electrical problems that MIDNIGHT SUN experienced during the race involved the most sophisticated (and most vulnerable) components of the solar car; specifically the onboard computer and the maximum power point trackers. Appendix C contains a description of the power system of the car. The onboard computer provided system monitoring (including a current integrator to indicate battery state of charge), vehicle speed or power cruise control, and real-time maximum power point tracking for the photovoltaic array.

On day 3 of the race, a power loss due to an electrical short resulted in an almost complete discharge of the silver-zinc storage battery. The short was found and fixed, but the battery voltage had already gone dangerously low. Adding to the problem was a two-day period of cloudy, rainy weather. At some point during day 3 or 4 of the race, the battery voltage dropped below the minimum input voltage (90 v) required by the 12 volt DC-to-DC power converter that was powering the computer and 12 v vehicle accessories of the car. As a result, the onboard computer lost power and stopped giving control signals to the four power converters attached to the four solar sub-arrays. This loss of control caused the control circuits on the four maximum power point trackers to be irreparably damaged by the power coming from the solar array. The computer also experienced some damage.

After the loss of the power point trackers, the array was reconfigured from four separate subarrays (each with its own power tracking and DC-to-DC converter) into only two subarrays of 350 cells in each. These two subarrays were connected directly across the silver-zinc battery, so that the operating voltage of the array was

fixed to the battery voltage.

Although the battery voltage fluctuated between about 111 volts and 145 volts depending upon whether it was being charged or discharged, the direct connection of the solar array to the battery worked very well for the rest of the race. The V_{oc} of each 350-cell subarray was about 192 volts, high enough that the battery voltage kept the array working in a region of the current-voltage curve where the current delivered to the battery was relatively independent of battery voltage. During one of the evening charging periods during the race, the power output of the array, connected directly to the battery as described, was determined by one of the US DOE observers to be approximately 800 Watts.

As described in Appendix C, a bypass diode was connected across each 12-cell module in the array to prevent the failure of one module from opening the circuit and pulling a whole subarray out of service. During a maintenance stop on Day 8, a reduced charging rate from one of the subarrays was detected, and several of the bypass diodes were found to be hot, indicating that they were passing current. One cold solder joint was found on one of the module connections. Several bypass diodes on other modules were found to have failed, and had the effect of shorting the modules they were connected across, even though the modules which they were supposed to have been protecting were functioning normally.

The exact cause of the diode failures remains unknown. However, it is possible that the following considerations were contributing factors. The diodes that were initially installed were rated at 200 volts and 20 Watts. The elevated temperatures inside the car (the diodes were attached to the underside of the car top) would have reduced the service rating of the diodes. During periods of charging, the battery voltage was often above 140 volts. The V_{oc} of one of the MIDNIGHT SUN PV cells

is about 0.50 volts at 60 °C and 0.64 at 0 °C. During the race, the average V_{oc} per cell on one module was measured as 0.55 volts. For these cells, the "knee" voltage (above which the cell current drops quickly with increasing voltage) corresponding to a V_{oc} of 0.55 volts is 0.41 volts. If only one 12-cell module failed, and the bypass diode operated, the average voltage drop across the remaining 338 cells in the subarray would be 0.41 volts. If more than one module failed (even intermittently) the average voltage across the remaining cells in the circuit would be higher, and the current delivered to the battery would be decreased.

If several of the inter-module solder connections had fatigued due to vehicle vibration so that they intermittently opened the circuit, then the bypass diodes for these modules would have had to intermittently carry the subarray current. It is possible that capacitive effects in the array could cause high momentary currents through these diodes, especially if the connections were broken intermittently as the car rolled along a bumpy road. The combined effect of the intermittent current through the diodes, and the high temperatures inside the car may have resulted in the diode failures. The intermittent nature of the solder joint contact would explain why there were several failed diodes across modules that tested all right when the car was not moving.

As a result of these diode failures, on Day 9 of the race all the original bypass diodes were removed and replaced by diodes rated at 6 amps and 600 volts (which were physically about 3 times the size of the original diodes). No problems with bypass diodes were experienced after that.

3.3.3 "The Accident"

MIDNIGHT SUN was involved in a well-publicized road accident on July 18, 1990. The UW car was in 17^{th} place overall at the end of Day 9 (July 17). At about 11:00 am on Day 10 the Waterloo car was about five miles south of the city of Van Wert on US Road 127 in Ohio, traveling north at 60 km/hr, when it was bumped off the road by an out of control pickup truck. The pickup truck was in the process of passing the MIDNIGHT SUN, when it slowed down beside the solar car and failed to avoid oncoming traffic. The back end of the pickup truck struck the left side of the solar car near the front, lifting the front of the solar car and directing it (airborne) into a smoothly sloped five foot deep ditch. The solar car driver was not hurt. Damage to the solar car resulted primarily from its collision with the ground at the bottom of the ditch, and included crushed front wheels and wheel faring supports, a broken bolt on the steering linkage, some damage to the rear wheel drive train, and some cracked solar cells.

Despite the difficulties, the next day MIDNIGHT SUN was repaired and driven across the finish line at the ceremonial finish of the GM SUNRAYCE USA at the GM Technical Center in Warren. After receiving time penalties for not completing the last day and a half of the race, MIDNIGHT SUN was awarded 24^{th} place with an official cumulative time of 114 hours 37 minutes and 15 seconds.

The primary factors contributing to the safety of the MIDNIGHT SUN driver in this accident were the strength of the car body and the fact that the driver was wearing a five-point driver restraint harness. The solar car body, make from TWARON cloth and epoxy resin over 6 mm thick foam, is light for its strength. In the side impact that the car experienced, the small mass the car allowed it to be accelerated sideways without experiencing large inertial forces. As a result, damage

to the point where the pickup truck struck the solar car was limited to a scratch on some decals on the side of the car. The body of the car did, however, flex in the collision, and it shifted slightly on the car frame. The cracked solar cells were a result of this flexing.

It is a tribute to the students who designed and built MIDNIGHT SUN that this car is as safe to ride in as it has proved to be.

Chapter 4

TEAM STRUCTURE

4.1 Structure

A hierarchical structure (Figure 4.1) was developed to administer this project. Students working in their specific disciplines reported all progress to their respective group leader. The three group leaders, responsible for vehicle design, electrical systems and logistics, then reported directly to the team leader and to the two faculty advisors, Professors Brunger and Lambert. The faculty advisors provided guidance when required to all team members, and served as the necessary link to the university administration. The team leader, Marc Gagnon, also interacted with various industry and university consultants, acting as the liaison between the two.

The three main consultants who aided the team leader with fund-raising were George Daszkowski, (Past) President of Waterloo Engineers in Toronto; Paul Spafford, Vice President Mergers and Takeovers, Wood Gundy; and Don Livingston, Director of Development and Alumni Affairs, U. of Waterloo.

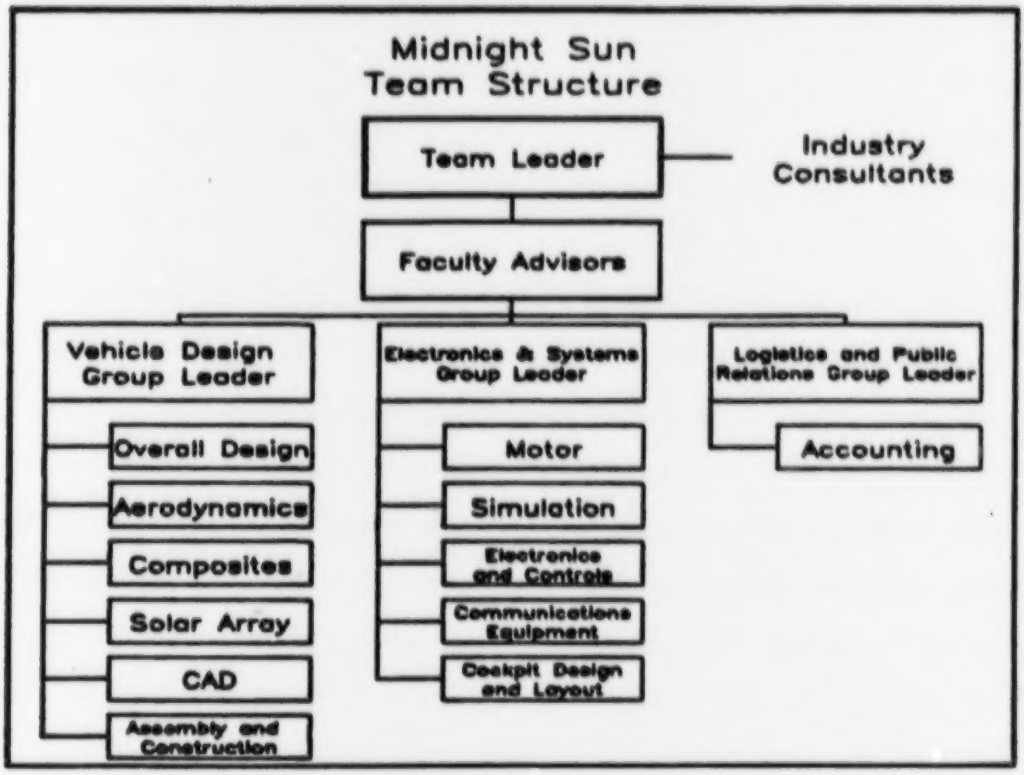


Figure 4.1: MIDNIGHT SUN team structure. (Taken from *A Final Report on Organization and Fundraising for 'MIDNIGHT SUN' the University of Waterloo's Entry in GM SUNRAYCE USA*, by Marc Gagnon. A report prepared for course ME 482 in Mechanical Engineering, U. of Waterloo, Spring 1990.

4.2 Team Members

Jeff Baker	Mechanical Eng. (Grad.)	Vehicle Construction; logistics.
Sheri Brown	Kinesiology	Cockpit design and layout.
Alfred Brunger	Mechanical Eng. Prof.	Faculty Advisor
Bradley Childs	Physics (Grad.)	Solar array
Julian Ford	Systems Design Eng.	Computer hardware and software.
Mark Gagnon	Mechanical Eng.	Team Leader.
John Hindson	Systems Desing Eng.	Power electronics.
Frank Kamler	Mechanical Eng. (Grad.)	Vehicle concept, frame design.
David Kelly	Mechanical Eng. (Grad.)	Composite materials for body.
Steve Lambert	Mechanical Eng. Prof.	Faculty Advisor
Jonathan Lawrence	Mechanical Eng. (Grad.)	Vehicle construction.
Rob Leslie	Mechanical Eng.	Group Leader: logistics and P.R.
Karen Levitt	Mechanical Eng. (Grad.)	Frame stress analysis.
Shawn Marshall	Mechanical Eng.	Group Leader: vehicle design.
Craig McEwen	Mechanical Eng. (Grad.)	Vehicle aerodynamics.
Ian Morrison	Mechanical Eng. (Grad.)	Motor.
David Pintur	Mechanical Eng. (Grad.)	CAD model development.
Glen Pyke	Systems Design Eng.	Computer hardware.
Karl Rueb	Systems Design Eng.	Group Leader: Electronic Systems.
Jordan Smith	Physics	Motor and power electronics.
Ray White	Mechanical Eng.	CAD model development.

Chapter 5

FINANCIAL OVERVIEW

The budget for the MIDNIGHT SUN project underwent several reviews, and at the end of the project stood at $120 400. The expenses and revenues for the project are shown in Tables 5.1 and 5.2.

The values for the expenses were calculated for each of the items listed in Table 5.1 by adding together the the sum of receipts acquired, the value of donated goods, and the estimated miscellaneous costs. This method gave a relatively accurate estimation of the total costs associated with each individual component of the vehicle.

The values given in Table 5.2 for the cash revenues are the actual amounts that were received from the corporations and organizations listed. The values listed under the heading of goods and services are the estimated values of such items that were donated to the project by the corporations indicated in parentheses.

Table 5.1

(From Marc Gagnon's ME 482 report. See caption to Fig. 4.1.)

EXPENSES

VEHICLE	
Chassis (suspension,wheels & brakes)	$ 7800.00
Body (composite, paint, etc.)	$ 16000.00
Motors (main & backup, incl. controller)	$ 14000.00
Power Electronics (trackers, power supplies)	$ 5000.00
Batteries (silver-zinc and lead-acid)	$ 24500.00
Cockpit Equipment (safety, computer, etc.)	$ 8500.00
Solar Array (incl. pv cells and lamination)	$ 10100.00
MISCELLANEOUS	
Communications Equipment	$ 5100.00
Testing Equipment	$ 2500.00
Promotional	$ 4500.00
Tools	$ 2750.00
Equipment Trailer	$ 5900.00
TRAVEL	
Accommodation,Living and Travelling Expenses	$ 9250.00
Recreational Vehicle	$ 2500.00
Support Vehicle	$ 2000.00
TOTAL EXPENSES	$120400.00

Table 5.2

(From Marc Gagnon's ME 482 report. See caption to Fig. 4.1.)

REVENUES

CASH

G.M. Seed Money (US$5000)	$ 6000.00
Energy Mines and Resources	$ 5000.00
University Alumni	$ 4500.00
U.S. Department of Energy (US$2000)	$ 2400.00
Northern Telecom	$ 2000.00
CAE Industries	$ 1500.00
D.O.E Sportsmanship Award (US$600)	$ 720.00
Society of Automotive Engineers	$ 700.00
SKF Bearings	$ 250.00
John Labatt	$ 10000.00
Sears Canada	$ 10000.00
University of Waterloo (unconfirmed)	$ 31580.00

GOODS AND SERVICES*

Composite Materials (AKZO)	$ 7500.00
Epoxy (Sternson)	$ 5000.00
Structural & Conventional Materials (Atlas)	$ 2000.00
Engineering Machine Shop Time (U of W)	$ 2500.00
Bearings and Miscellaneous (SKF)	$ 1000.00
Comm. Equip. (Northern Telecom & Motorola)	$ 4000.00
Power Supplies (Vicor)	$ 1000.00
Tattletale Microprocessor (Onset)	$ 500.00
Logos (Freebird Graphics)	$ 1000.00
Eyewear (Corning Optics)	$ 2250.00
Tool Set (Sears)	$ 2500.00
Uniforms (Sears and Labatts)	$ 1500.00
Pick-up Truck (Stedlebauer Chev-Olds)	$ 2000.00
Laptop computers (Zenith Data Systems)	$ 4000.00
Miscellaneous	$ 2000.00

STUDENT FUNDRAISING

Pubs, Raffles and Novelties	$ 5000.00
Student Societies	$ 2000.00

TOTAL REVENUES	$120400.00

* All items over $500 are listed, all others have been combined into the Miscellaneous category.

Chapter 6

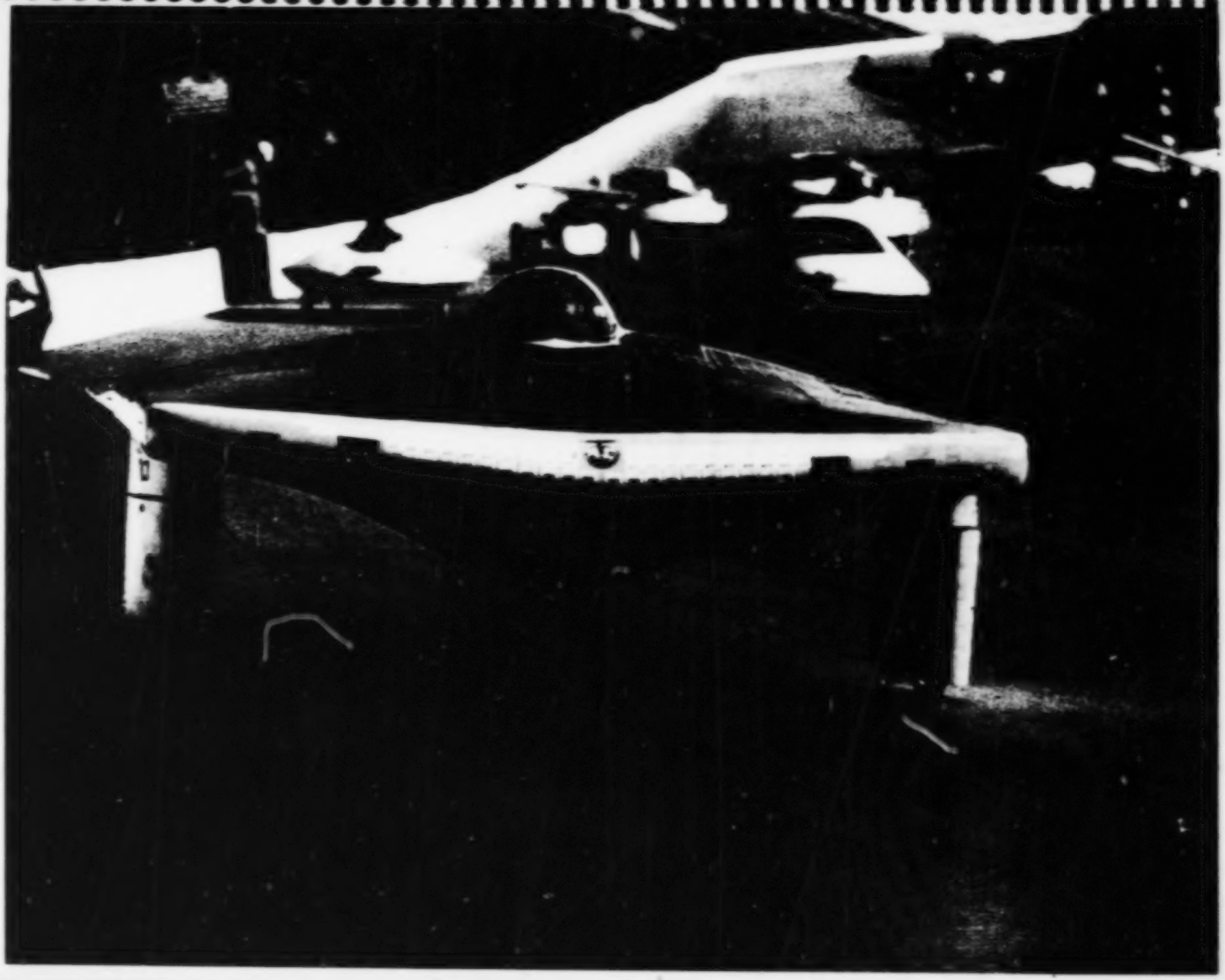
SUMMARY

The University of Waterloo solar car MIDNIGHT SUN proved to be a competitive entry in the 1990 GM SUNRAYCE USA. Notwithstanding the problems that had to be solved during the course of the actual race, the whole project was successful in that the major goals of giving students exposure to solar energy and automotive technology, and of interesting the public in solar energy and in engineering and science in general, were fully achieved.

Appendix A

The MIDNIGHT SUN Solar Car

This picture was taken by Jeff Baker during the GM SUNRAYCE USA when the solar cars were on the Indianapolis Motor Speedway in Inianapolis, Indiana, on July 17, 1990. The driver of MIDNIGHT SUN at Indianapolis was Mark Gagnon.



Appendix B

"Organization and Fund-Raising for 'MIDNIGHT SUN'—The University of Waterloo's Entry in GM SUNRAYCE USA"

This paper was presented in the CSME Minisymposium on Mechanical Engineering Education held as part of CSME Mechanical Engineering Forum 1990, June 3–8, 1990 in Toronto. (Paper number MEE-10.)

ORGANIZATION AND FUND-RAISING FOR 'MIDNIGHT SUN'—THE UNIVERSITY OF WATERLOO'S ENTRY IN GM SUNRAYCE USA

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ABSTRACT

GM SUNRAYCE USA, a solar powered car race in July 1990, will run approximately 1613 miles from Walt Disney World in Florida to Detroit, Michigan. The Midnight Sun team from the University of Waterloo will be competing against students from 31 other North American universities. The Midnight Sun project is the largest student project ever undertaken by the University of Waterloo, with a budget of $116 400 and the involvement of over 25 undergraduate and graduate students and two faculty advisors. A hierarchial structure has been developed to administer this project. Several strategies for obtaining sponsorship have been pursued. This paper discusses these organizational and fund-raising activities, as well as some of the advantages and pitfalls associated with such a large student project. It has been found that it is much easier to obtain donations in kind than to get cash donations from sponsors, and that individual motivation and formal lines of communication are important to the success of the project.

1. BACKGROUND TO THE GM SUNRAYCE USA

In February, 1990, a group of senior mechanical engineering students at the University of Waterloo responded to a request for proposal from General Motors to enter the 1990 *GM SUNRAYCE USA*. *GM SUNRAYCE USA* will be an 11 day, solar powered vehicle race covering approximately 1613 miles, from the GM World in Motion Pavilion at Walt Disney's EPCOT Center in Orlando, Florida, to the GM Technical Center in Detroit, Michigan. Participation in the race is restricted to North American educational institutions, including colleges, universities and trade schools. In April, 1990, the University of Waterloo was notified that it was one of 32 schools selected for participation. The University of Ottawa was the only other Canadian school selected. GM will send the top three teams to compete in the World solar Challenge in Australia in November, 1990.

General Motors has decided to sponsor this race to provide a forum for technical innovation and participation for students. The increased public awareness is intended to encourage more young people to pursue technical careers. They have chosen solar powered vehicles to emphasize the need for environmentally sound technologies, and to highlight the potential of solar energy.

All vehicles must conform to the World Solar Challenge rules. Some of the basic specifications include restrictions on maximum vehicle size (5 m long by 4 m wide by 1.6 m high), maximum solar array size (4 m by 2 m by 1.6 m), maximum battery storage capacity (5 kilowatt hours), and minimum driver mass (80 kg). To ensure that the design is a student effort, GM further requires that the design team be composed of at least 50 percent undergraduate students and only one or two faculty advisors, and that only limited consultation from outside industry be used. Each team is responsible for all of the costs associate with the design, construction and participation in the race. However, to provide initial assistance, GM and the US Department of Energy have given each team a total of $7000(US) in seed money.

The design for the University of Waterloo vehicle, *MIDNIGHT SUN*, is illustrated in Figure 1. The vehicle is driven through the single rear wheel and steered via the two front wheels. The design has evolved in the first 8 months of the project, with construction scheduled to begin in earnest in January 1990. As of January 1990, about one third of the $116 400 budget has been secured; more than half of this is in the form of donated goods and services.

The primary objective of the *MIDNIGHT SUN* team is, of course, to win the US competition and secure a berth in the World Solar Challenge. In addition, it is intended to be an educational experience in organizing and participating in a large engineering project. To meet these objectives, a formal organizational structure has been developed to facilitate a consistent and uniform effort by all team members. Due to the high cost of such a project, a systematic fund-raising strategy has been developed. The organization and fund-raising will be described separately below.

2. ORGANIZATION

2.1 Introduction

Despite past and ongoing participation in several large engineering

Figure 1: Overall view of the MIDNIGHT SUN solar vehicle.

Figure 2: Organizational structure of the MIDNIGHT SUN team.

design competitions, including the *Shell Pushathon*, the *Formula SAE*, and the *SAE Mini Baja*, *GM SUNRAYCE USA* is the largest student project ever undertaken by this university. It holds this distinction as a consequence of the level of effort required, the number of students involved and the size of the required budget. To satisfy the scope of this project, undergraduate and graduate students from several academic departments have become involved; these include Mechanical Engineering, Systems Design Engineering, Electrical Engineering, Kinesiology, and Physics. To satisfy requirements for expertise not within the university, outside consultants have also been engaged. These individuals have assisted with both technical and non-technical aspects of the project; for example, solar module construction and fund raising.

2.2 Implementation

The hierarchial structure shown in Figure 2 has been developed to administer this project. The executive consists of one overall team leader, three group leaders, and two faculty advisors. The team leader is responsible for the overall co-ordination of the project and for fund-raising. The three group leaders are responsible for vehicle design, electrical systems, and logistics. Faculty advisors provide guidance and the necessary link to the University administration to facilitate the purchasing of outside materials and services and to obtain the use of university space and equipment. Both faculty advisors have past experience supervising major student projects; one has experience in solar energy and the other has experience with vehicle design.

The team leader and one of the faculty advisors form the official link with GM to discuss technical and logistical concerns as they develop. This information is passed through to the group leaders as necessary. Students working in any of the sub-groups report all progress to their respective group leaders.

General team meetings are held approximately once a month to report on progress, discuss possible problems and to set goals for the near future. As required, outside consultants are invited to participate in these general meetings. The contents of regular newsletters from GM and other general information are discussed at these meetings, attached to copies of the minutes, and made available to all team members.

2.3 Discussion

The hierarchial structure developed for this project provides a mechanism for administration and communication within the team. The effectiveness of this structure has improved markedly over the first 8 months of the project as the team has become more cohesive and team spirit has increased. Initial efforts were exasperated by the fact that key team members were distributed throughout Ontario during a workterm arranged prior to participation in this project. Efforts were made to ensure that these key members were on-campus during the next workterm, beginning January 1990.

Although the administration and communication are adequate, there remains very little actual control. As discussed later, many students are acting strictly as volunteers, with no academic rewards (or penalties). The only control mechanisms remaining, therefore, are enthusiasm and peer pressure. For example, despite the fact that this was intended as a group design effort, one student dominated the design phase through his enthusiasm, sustained level of effort, and past experience. Initially, other members of the design team were overwhelmed. Their role increased toward the latter stages of design through analysis and criticism of the design as their confidence increased.

Another problem occurs when students under-perform. A formal team structure and rapid communication are necessary to discover such situations at an early stage, before they jeopardize the success of the project. When it is impossible to get the student sufficiently motivated, his work must be distributed onto other students. This situation has occurred and was not adequately at the sub-group level. At the time of writing, vehicle construction is underway and a more rigorous method of monitoring individual progress is being pursued.

3. FUND-RAISING

3.1 Introduction

As a result of the scale of this project, careful planning and extensive effort were required in all aspects of fund-raising. In general, cash, goods and services were required. Straight monetary donations are by far the most difficult to obtain. The following sections outline the basic strategy in fund-raising including the budget, support from both outside and inside the university, and publicity.

3.2 Budget and Cash Flow

The initial budget for this project, as presented in the February, 1989 proposal, was about $22 000. Preliminary discussions with GM (after acceptance of our proposal) and the realization of the level of competition forced us to revise our budget upward. Currently, the budget exceeds $100 000 as listed in Table 1. The increase resulted from significant increases in estimates for key items such as the batteries, motors, and solar cells. In addition, to reduce the impact of possible last minute problems, the budget includes provisions for spare components and for cheaper test versions of some components. For example, two complete motors and one set of lead acid batteries (used for testing only) are included in the present budget. The prices for most items have been over-estimated to accommodate administrative costs such as long distance phone, fax, and shipping charges associated with the sourcing and acquisition of the various components, as well as taxes. These estimates are continually being refined as items are purchased or sourced.

Table 2 lists the expected sources of income for the project. These revenues include cash, goods and services. The cash revenues, except for the remaining corporate sponsorship, are the actual levels of support secured to date. At the time of writing, $10 000 of the required $70 000 corporate sponsorship has been secured. The goods and services listed have also been secured; values are estimates only. This list

Table 1: Current Budget

VEHICLE EXPENSES:	
Chassis	$5500
Body	7500
Motors	15000
Power Electronics	8000
Batteries	25000
Cockpit Equipment	4500
Solar Array	25000
MISCELLANEOUS EXPENSES:	
Communications Equipment	$3500
Testing Equipment	2500
Promotional	3500
Tools	1000
Vehicle/Equipment Trailer	2900
TRAVEL EXPENSES:	
Accommodation and Living	$12600
Support Vehicles	2600
TOTAL EXPENSES:	$116400

Figure 3: Cumulative cash requirements and revenues.

is being updated as revenues become available or dry up.

Not obvious from these tables is the required cash flow. That is, not only must the ultimate revenues match the total expenses, but they must also arrive in a timely fashion. In Figure 3, the cumulative cash requirements and revenues for the project are plotted in a bar chart as a function of time. The estimated schedule of expenses is complete to race day. Secured revenues have thus far kept pace with actual expenditures. However, to cover any gaps between the securing of revenues and their actual delivery, an interest free loan was negotiated with the Dean of Engineering. This provides a cushion to keep the project afloat while waiting for promised revenues. In addition, it allows the ordering of long lead-time and expensive items, such as the batteries, with some measure of confidence.

2.2 Outside Support

Outside support includes the supply of cash, goods and services from industry and government. A necessary first step in obtaining such support is to establish both the contacts and the strategy to approach potential sponsors. Despite the relative youth of the University of Waterloo, we have been greatly assisted by alumni. Several individuals in particular have acted as councilors and champions for our cause.

Table 2: Estimated Revenues

CASH:	
GM Seed Money (US$500)	$4 050
US Department of Energy (US$2000)	2 400
Energy Mines and Resources, Canada	5 000
Northern Telecom	2 000
John Labatt's	10 000
Remaining Corporate Sponsorship	70 000
GOODS AND SERVICES:	
Composite Materials (AKZO)	$5 000
Structural and Conventional Materials (Alcan Alloys)	2 000
Machine Shop Time (U of W)	1 500
Bearings, etc. (SKF)	1 000
Communications (Northern Telecom and Motorola)	3 000
Miscellaneous	2 500
STUDENT FUND-RAISING:	
Pubs, Raffles and Novelties	$5 000
Student Societies	1 000
TOTAL REVENUES:	$116 400

These include George Dambkowski, president of Waterloo Engineers in Toronto, and Paul Spafford, a Vice-President for Wood Gundy. Our success thus far can largely be attributed to these two individuals.

As mentioned, the donation of goods and services were readily obtained in most cases, often through alumni or contacts made by students on workterms. The companies involved often requested little in return. As a minimum acknowledgement, however, a list of contributors, along with pictures of the vehicle as it progresses, is posted in a display case at the university. In addition, the names of these minor sponsors will be displayed on the trailer used to transport the solar vehicle.

Larger cash donations require more substantial forms of acknowledgment. To avoid conflict with ongoing general university fund-raising activities, cash donations are only accepted in exchange for advertising space on the solar vehicle. Initially, attempts were made to find a single sponsor willing to underwrite the entire project. These attempts were unsuccessful due to the large amount of money required and the lack of sufficient high-powered contacts. Therefore, a more flexible strategy involving several major sponsors was developed.

Due to the aerodynamic shape of the vehicle and the fact that the entire top surface must be covered by solar cells, relatively little space is available for advertising. The current strategy is to create a panel on each front wheel fairing with the team logo at the center, and surrounded by ten advertising spaces, Figure 4. This presents a clean, professional appearance. These spaces are offered to potential sponsors for $10 000 each, with no limit on the number of spaces that can be purchased. In addition to the $10 000 basic cost, sponsors are requested to set aside a further $5000 per space as contingency money. This strategy, recommended by Paul Spafford, has been instituted to ensure that the project does not fail due to some last minute financial problems due to unforeseen circumstances. These extra funds have not been included in our budget, but will be available to accommodate last minute cost over-runs.

A sponsorship agreement has been drafted to ensure that potential sponsors have a clear understanding of their rights and obligations. This agreement acknowledges that these ten sponsors are the sole sponsors of the *MIDNIGHT SUN* vehicle, and guarantees that their logo will be present on the vehicle and on the team member uniforms at all times during the race. The term of the sponsorship agreement is limited to the period before and during the 1990 GM SUNRAYCE USA. This ensures that the team members and the university are not obliged to carry on any promotional activities after the race, but leaves open the possibility of obtaining further sponsorship (from the original or other sponsors) to provide funds for future events

Figure 4: Team logo with surrounding advertisement space offered to major sponsors.

that the *MIDNIGHT SUN* team may wish to participate in.

At present, two of the ten advertising spaces have been committed. One has been purchased by John Labatt's Corporation, and one will be shared by Energy Mines and Resources, Canada, and by AKZO international.

3.4 University Support

The university has supported the *MIDNIGHT SUN* team in several ways. As mentioned, the Dean of Engineering has provided a $20 000 loan to help with cash flow for the project. In addition, he has arranged to fund one student for a work term beginning in January, 1990, so that the student may work full time on the construction of the vehicle. The Department of Mechanical Engineering has provided office space for the team, and a large lab area for vehicle construction. The faculty of engineering has a well equipped student shop where much of the machining can be performed by the students under the supervision of a full time technician. More complex machining tasks will be performed by the professional machinists in the Engineering Machine Shop, with the majority of the cost of such machining being underwritten by the Faculty of Engineering.

3.5 Student Fund-raising Activities

Student fund-raising activities include the holding of pubs and the selling of T-shirts printed with the phrase *"I'm driven by the Sun"*. While these student fund-raising activities, of necessity, will form only a small proportion of the overall budget, they are important in improving school and hence team spirit. Although the co-operative education system has many advantages, alternating four month academic and workterms can upset social contact necessary to foster good school spirit. These student activities also raise the profile of the project around campus, which helps further fund-raising off campus.

3.6 Publicity

An important and integral part of any fund-raising campaign is adequate publicity. This is especially true where contributors are promised advertising in exchange for donations. The emphasis in the publicity campaign must shift as the project progresses. Initial attempts were directed primarily at increasing the degree of awareness of the project and at attracting suitable sponsors. As time passes, and (hopefully) more sponsors commit themselves, continued publicity is necessary to ensure that these sponsors have adequate return on their investment. Such continued publicity will be aided by the high profile that the race has been given and will receive as a result of the professional efforts of GM through the GM SUNRAYCE USA headquarters.

The local publicity campaign is active on several levels. At key intervals, progress reports will be prepared and press releases given to the local newspapers. Presentations have been made to student societies and to community groups, including public schools. Slides of the Computer Aided Design (CAD) drawings of the vehicle concept were shown at a CAD user's group conference in the US. This presentation attracted much interest; one company volunteered to make a CAD-based animated video, to be used in further presentations. Attempts have been made to attend several trade shows. The first public unveiling of the vehicle concept took place at the *Our World, Environmental Summit*, held in Toronto in December. This produced several contacts and provided us with national TV exposure (and an opportunity to meet the premier of Ontario!).

Conflicting requirements for widespread publicity to enhance fund-raising and maintaining a low profile to keep competitors guessing were met with a suitable (Canadian) compromise. A two-tiered approach was adopted wherein the vehicle was unveiled in Canada in September, 1989, and the US and world unveiling was delayed until January, 1990. Pictures of the vehicle will be presented at the Detroit auto show in a booth set up by GM for all competitors. An attempt is being made to present our partially constructed vehicle at the Toronto Auto show in February, 1990.

4. UNIVERSITY CONCERNS

4.1 Academic Issues

The *MIDNIGHT SUN* project is too large to fit into the normal program of a single Engineering department or into the normal scope of a one or two-term project course. Therefore, the support at the Faculty level is critical, as is the co-operation of faculty members in several departments. Still, a significant proportion of the undergraduate students involved, and all of the graduate students, are contributing their time freely, with no hope of academic credit. An advantage to this situation is that more students are able to participate in, and learn from, this interesting engineering project, since not all students would be in a position to be able to commit one whole academic course to the project. As mentioned, however, there is the disadvantage of it being more difficult to sustain interest levels in the absence of academic credit for the efforts being spent.

Fortunately, the overall the project can be broken down into smaller tasks, which can be completed within the normal project course set-up. Typical examples of such sub-tasks are: computer aided design of the vehicle shell (Mechanical Engineering), optimum control strategies for operation of the vehicle (Systems Design Engineering), and design of the cockpit and driver display panels (Kinesiology).

The co-operative education system at the University of Waterloo helps in two ways: students make contacts in industry that they can use when working on this project, and co-op students can be available on campus or near by so they can continue to work on the project in their "off terms" when they have more free time.

4.2 Fund-raising Issues

The University administration is (rightly) concerned with groups within the University making requests for money from outside organisations who may be significant corporate donors to the University as a whole. For major projects in general, the University accepts such solicitation so long it is made clear to potential contributors that it is for a student initiated project. Such solicitation by the *MIDNIGHT SUN* team could still cause problems due to the magnitude of support required. Therefore, all cash donations are considered as payment for advertising, thereby avoiding encroachment on company budgets set aside for donations to non-profit organizations, and eliminating the need for the University to issue receipts for non-taxable donations.

4.3 Liability Issues

From the start of this project, we have been mindful of risk management issues as they pertain to the project. For the most part, the work done by students is done on campus, and is covered by the

general liability insurance policy of the university. However, since the solar vehicle will be traveling on public roads, a separate vehicle liability insurance policy is required. The university purchasing department has been helpful in the procurement of such a policy.

Another issue concerns the liability of faculty advisors. After provision for the safety of students working on the project, the main concern is for the control of spending. Although it may be unlikely that the faculty advisors would be held personally liable by the University for any excess of expenditures over revenues for the project, nevertheless it is the advisor's responsibility to protect the university from over-expenditures. A trust account has been set up for this project, and all revenues and expenses for the project are monitored by the Administrative Assistant of the Department of Mechanical Engineering, and by one of the students on the team. As a way of ensuring control, the two faculty advisors for the project, and none of the students, have signing authority on this trust account.

5. CONCLUSIONS

At the time of writing, January 1990, the vehicle design is fixed and construction has begun. Most major subsystems have been designed and the parts ordered. More than one third of the total budget has been raised; most of this in the form of goods and services. The student leader is currently working full time on vehicle construction and fund-raising. It is recognized that the presentation of a rolling vehicle is an important step in the project, and may be necessary to obtain the remaining funds. With this is mind, deadlines have been established: the end of February for the presentation of a rolling vehicle, and the end of April for the initial testing of the complete vehicle. Since, the project is still underway, the following conclusions should be considered preliminary.

It has proven to be much more difficult to obtain cash from corporations than to obtain goods and services; this is particularly so for the relatively large minimum amount requested—$10 000. Almost all goods and services have been obtained through personal contacts; most of these have been through alumni. This has been particularly rewarding given the relative youth of the University of Waterloo.

A large project such as this needs a commitment from groups and individuals to produce high quality work on time. With relatively little to control this, group leaders must rely on motivation to ensure performance. To spot potential trouble spots, communications must be effective.

The sheer size of this project, and the sustained level of effort required of all key participants, is such that it is unlikely that a given department or university can afford to undertake such projects on a regular basis.

ACKNOWLEDGEMENTS

The generous support for this project provided by the Faculty of Engineering of the University of Waterloo through Dean Bill Lennox, by George Daszkowski and Paul Spafford and by the following government and corporate organizations is gratefully acknowledged. Air Link Atmospheric System; AstroPower Canada Ltd.; Atlantic Packaging Products Ltd.; Atlas Alloys; Energy, Mines and Resources, Canada; General Motors; General Motors of Canada; John Labatt's Ltd.; McQuest Marine; Mr. Gas Limited; Northern Telecom; PowerPlex; SKF Canada Limited; U.S. Department of Energy.

Appendix C

"Design Considerations for a Solar Car PV Power System"

This paper was presented at "Sustainable Energy Choices for the 90's," 16th Annual Conference of the Solar Energy Society of Canada Inc., June 18–20, 1990 in Halifax. (Proceedings pp. 9–13.)

Presented at "Sustainable Energy Choices For The 90's"
16th Annual conference of the Solar Energy Society of Canada Inc. June 18-20, 1990.
Halifax, Canada. pp. 9-13.

DESIGN CONSIDERATIONS FOR A SOLAR CAR PV POWER SYSTEM

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ABSTRACT

Although solar powered cars are not ready to replace existing automobiles, studies in this area can provide useful information for consideration with all solar powered vehicles. This paper describes the design considerations relating to the PV power system of MIDNIGHT SUN, the car from the University of Waterloo entered in the GM SUNRAYCE USA. The power system described is for a solar powered race car which was designed to meet race rules. The design considerations, in the most part, concern maximizing energy efficiency. Three means of maximizing the energy delivered by the MIDNIGHT SUN PV system are described: cell lamination with ETFE film to reduce reflective losses; the use of maximum power tracking to follow the PV array's best operating point during the quickly-changing irradiance conditions expected; and the use of high efficiency, low mass silver-zinc batteries. The PV array was divided into four sections to partially compensate for the non-planar shape dictated by aerodynamic considerations.

1 INTRODUCTION

GM SUNRAYCE USA, which will be held in July 1990, is an eleven day, 1800 mile, solar powered electric vehicle race from Florida to Michigan. In a selection made from competing proposals, the University of Waterloo was chosen by General Motors as one of 32 academic institutions from across North America to be invited to participate in this race. The top three teams in the GM SUNRAYCE USA will be sponsored by GM to compete in the World Solar Challenge in Australia in November, 1990. A multi-disciplinary student project has been set up at the University of Waterloo to design, build and race a vehicle named MIDNIGHT SUN, which will be the University of Waterloo's entry in the GM SUNRAYCE USA. This paper describes the photovoltaic power system used in MIDNIGHT SUN, and discusses some problems peculiar to the application of PV technology to this racing vehicle.

2 CAR DESCRIPTION

MIDNIGHT SUN is an efficient solar-electric vehicle. The electric power to operate the car is provided by photovoltaic (PV) cells which directly convert solar radiation into electricity. The power system for MIDNIGHT SUN is essentially a stand-alone PV power system. For a solar race car, even more so than for a stationary PV system, the goal is to maximize the total deliverable energy while staying within the constraints imposed. For the GM SUNRAYCE USA, the race rules put constraints on the PV array size and on the battery capacity. The solar array must fit into a 2 m by 4 m by 1.6 m box. Converted solar energy may be stored in batteries for later use, but the battery capacity is limited to a maximum of 5 kWh. A three phase AC induction motor is connected to the single rear drive wheel to provide motive force. The details of the motor and motor controller are not discussed in this paper.

Figure 1: Computer-generated image of MIDNIGHT SUN.

As with most energy efficient vehicles, the aerodynamics of MIDNIGHT SUN are very important. Since most of the race is expected to occur at highway speeds (up to 90 km/h), MIDNIGHT SUN has been designed to be as aerodynamically efficient as possible. The vehicle shape was influenced only slightly by array power considerations. For this reason the solar array is not flat as most stationary solar collectors are. A maximum difference in orientation of 30 degrees exists from cell to cell. Each PV cell has a different orientation and therefore responds differently to a given solar irradiance condition. The PV array was divided into four sections to partially compensate for its non-planar shape.

3 DESIGN

The designs of three of the car's power system components are described in this paper: the solar array, the maximum power point trackers, and the battery system. The solar array is where the initial energy conversion occurs. The Maximum Power Tracker (MPT) is the power system component which makes it possible to maximize the total available power. The battery is where excess power is stored and from which energy is extracted for use by the motor during times when the power available directly from the array is insufficient.

3.1 Solar Array

The solar array for MIDNIGHT SUN is made up of 660 single crystal, silicon photovoltaic solar cells. The cells were manufactured by ARCO Solar, Inc. and have a conversion efficiency of approximately 13.4 percent. The manufacturer's data indicate that at 1000 W/m^2 irradiance and a cell temperature of 25°C, each cell will generate 3 amps at 0.5 volts giving a power output of 1.45 W. More than 660 cells could have been used in the main array of the car, but an important consideration in determining the design of the solar array was the complexity of the electronics. Any additional cells would have been situated in small, high curvature sections requiring costly, low efficiency electronics.

For ease of mounting and replacing broken cells, the cells are grouped into modules. Each module consists of twelve cells connected in series. The number of cells in a module was chosen to best suit the physical form of the array. If too many cells were used, the modules would have to have been curved when placed on the car; too few cells, and the complexity and quantity of connectors would have increased the mass of the car.

The modules are laminated with 0.46 mm EVA and 64 μm ETFE (Tefzel†). The laminating materials provide protection for the cells and improves the cell efficiency by reducing the reflective losses. The ETFE material was chosen because of its desirable optical properties. The more conventional lamination material, 0.1 mm PVF (Tedlar†), would provide the same protection as ETFE, but the efficiency would not have been as high. The ETFE has an index of refraction of 1.397 compared to 1.46 for PVF, which makes ETFE reflect about 1% less of the solar radiation than PVF does. Moreover, the 0.1 mm thick PVF absorbs about 3% more of the solar radiation than the 64 μm ETFE does.

The solar array consists of 55 modules. Each module is relatively flat (with less than a 4 degree angle between cells in the module) and positioned, in general, with a different orientation angle with respect the the other modules. One method of attempting to maximize the total power would be to have each module electrically separate from the other modules. However this would require 55 maximum power trackers, each requiring power to work. This power loss and the total mass of the trackers had to be considered when determining the number of sub-arrays into which to divide the array, since the most important consideration was to maximize the overall efficiency of the vehicle. By dividing the array into only four sub-arrays of 165 cells each, the differences in orientation between the cells of a single sub-array were kept reasonably small, and only four maximum power trackers were required.

All modules in each sub-array are connected in series to provide a high voltage and to limit the currents. The expected output of each sub-array is 80 volts at about 3.6 amps. Bypass diodes are connected in parallel with each module to prevent the failure of one module from pulling the whole sub-array out of service. A system that will sense the voltage across the diodes will be used to allow quick identification and replacement of failed modules.

†Registered trademark of Du Pont.

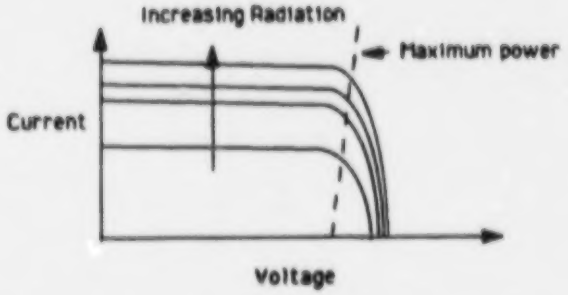

Figure 2: Current versus voltage for a solar cell.

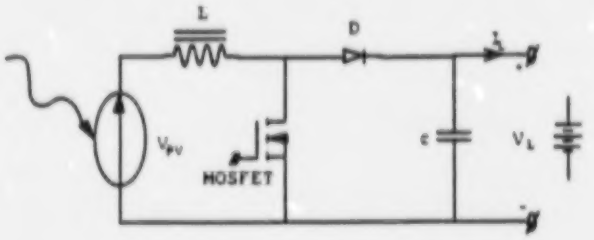

Figure 3: DC to DC boost converter. (Adapted from [1].)

3.2 Maximum Power Tracker

The Maximum Power Tracker (MPT) is an electronic device used to maximize the conversion efficiency of PV collectors. PV cells, when exposed to light, do not automatically convert sunlight to electricity at a fixed voltage and current. The voltage-current characteristics are best described using the current versus voltage curves in Fig. 2. Each curve is for a different sunlight condition. As shown on the figure, at low voltages the current remains relatively constant, but as the voltage approaches the OCV (open circuit voltage) the current rapidly decreases to zero. The power produced at any point on the curve is simply the product of the voltage and the current. The maximum power point occurs at a different voltage and current for each different radiation intensity. The irradiance on each module depends on the solar radiation intensity and its incident angle. The incident angle is the angle between a line perpendicular to the cell and a line pointing at the sun. Since MIDNIGHT SUN will be moving, the radiation intensities will be changing constantly. For this reason the maximum power point cannot be fixed at a specific point as with most stand-alone PV power systems, but instead must be actively tracked if the maximum power is to be achieved. Even if a set design voltage were to be chosen, and a battery sized to fix that voltage (which is the usual method), an electronic circuit would still be required since batteries do not maintain a constant voltage. The voltage of the battery used in MIDNIGHT SUN will vary from 90 to 148 volts, a range that is too wide for maintaining the PV power point near the maximum.

MIDNIGHT SUN uses a variable DC to DC boost converter (Fig. 3) with an active analogue tracking circuit following a design proposed by Salameh and Taylor [1] (Fig. 4). The converter is used to control the solar array current while allowing the input and output voltages to float (although the output voltage must be greater than or equal to the input voltage). The output voltage depends on the load. On MIDNIGHT SUN this is set by the batteries (90 to 148 volts). The converter could have been either a boost, or a boost/buck, or a buck converter. The buck converter converts a high input voltage to a lower output voltage. The buck converter would require sub-arrays which could no longer be relatively flat because of the large number

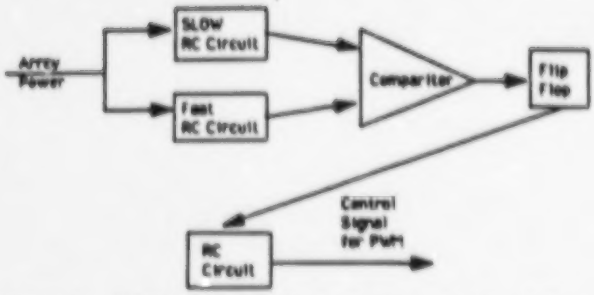

Figure 4: MPT controller block diagram. (Adapted from [1].)

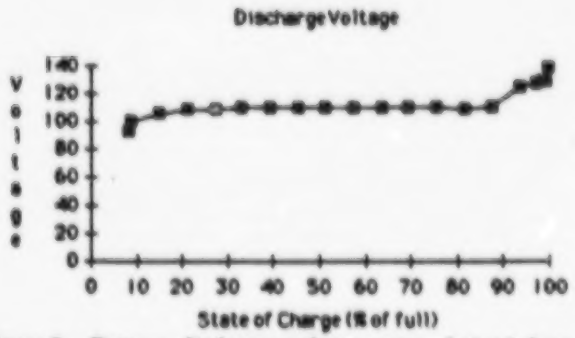

Figure 5: Battery discharge voltage curve derived from data provided by the battery manufacturer.

of cells which would be required to be connected in series to achieve a high enough input voltage. The boost/buck converter is more complex than was required. The boost converter would allow relatively flat sub-arrays with a voltage around 80 volts (13.75 modules). An efficient (>90%) converter can easily be constructed for this purpose. Designs can be obtained from most power electronics texts or made up by firms specializing in custom power electronics.

The goal behind the MPT is to set the input (PV) current to an unknown maximum power point value. The power point is found by an active searching circuit. The current is controlled by charging and discharging an inductor in the DC to DC converter. The switch in the converter is controlled by a pulse width signal generated by the searching circuit. The pulse width controls the proportion of time between charging and discharging. The PV voltage will be whatever is generated at the set current value. The output voltage will be set by the battery voltage. The following steps are involved in the analogue searching algorithm:

1. change the pulse width signal;
2. compare the present power to the previous power — using two resistor-capacitor circuits;
3. if the power is increasing, continue changing the pulse width signal;
4. if the power is decreasing, reverse the direction of change to the pulse width signal.

This algorithm is implemented in the block diagram in Fig. 4. The accuracy of the MPT depends on the time constants for the two resistor-capacitor circuits. The smaller the time constants and the smaller the difference between the two circuits, the closer the power point is tracked. The time constants must be large enough so as to not react to the small fluctuations occurring during the pulse width.

A considerable portion of the design effort on the MPT went into sizing the inductor. The inductor is a critical component because it represents most of the weight of the MPT system and it determines the amount of current ripple on the array (due to the charging and discharging of the inductor). A larger inductor gives the circuit a larger time constant which results in a smaller ripple. The smaller ripple allows the MPT to more closely track the maximum power point. Unfortunately, increasing the inductor size adds mass to the system, and increases the response time of the tracker. The electrical efficiency of the converter is also affected by the inductor size. With the help of an electronic component manufacturer, inductors of approximately 6 mH were chosen for this application.

The efficiency of the MPT depends on the quality of components, the power converted, the voltage boost, and the elimination of electrical resonance. A test converter of the type used in MIDNIGHT SUN has achieved an efficiency of 94.5%. Adjustments are expected to improve this efficiency. The total cost to manufacture eight MPT's will be less than $3,000.

3.3 Energy Storage

Unused energy is stored in a battery (an electrochemical, coulombic storage devise). Since this is used in a car, the battery had to be light-weight to reduce the car's rolling friction. In order to minimize energy waste, the maximum storage capacity of 5 kWh was chosen. MIDNIGHT SUN uses Eagle-Picher, silver-zinc batteries: 74 low rate, 45 amp hour 1.5 volt cells connected in series to provide a 4.995 kWh, 111 volt, 34.5 kg battery pack. The recommended charge/discharge rate for this battery is 222 watts. This rate can be pushed to higher rates at a cost of decreased efficiency and lifetime. The useful life of the battery is six months. The battery has a price of $23,000.

The efficiency of energy storage will vary from 97% down to 65% as the charge rates are increased from 222 watts to 2000 watts. In choosing this battery, several considerations were made. First, the maximum power that the motor can draw is 3 kW. This will only occur for short periods of time (accelerating up a hill): the goal is to drive as efficiency as possible. Second, the average expected power draw from the batteries would be less than 0.5 kW. Third, the main charging periods are at dawn and dusk with low charge rates expected (less than 0.5 kW). Fourth, the low rate silver zinc batteries were about 4.5 kg lighter than the high rate batteries. These considerations resulted in the choice of the low rate batteries.

Battery voltage rises during charging. To fully charge the battery pack this voltage must reach 148 volts, but if 148 volts is exceeded the batteries will be damaged. During discharge the battery pack output voltage is 111 volts. This voltage drops as the battery is discharged to about 5% of capacity. (See Fig. 5.) Further discharge below the 90 volt level could damage the batteries. This sensitivity requires accurate charge/discharge regulation. In order to aid in preventing charge/discharge damage, and to facilitate in determining race strategy, an energy gage is included in the car. This gage is implemented by the onboard computer integrating the product of the battery current and efficiency with respect to time. Overcharge regulation is incorporated into the MPT while undercharge protection is incorporated into the motor controller.

4 OVERALL OPERATION

The overall power system is summarized in Fig. 6. The Maximum Power Trackers will maximize the available power and provide overcharge regulation. The motor has a recommended voltage of 115 volts while the battery voltage will be 111 volts. Higher battery voltages will only occur during charging when there is excess power, during which times the motor efficiency can be allowed to decrease. The battery will store the excess power and provide this power when needed. The motor controller is implemented in an onboard computer which will provide undercharge protection and an energy storage gage for the battery.

Safety was given careful consideration in all parts of the car design, as is consistent with good engineering practice. MIDNIGHT SUN incorporates forced ventilation for the battery box; fuses and circuit breakers on all electrical subsystems; appropriate electrical insulation and high voltage signs; isolation switches for the array, the motor and the battery; and special circuits to prevent accidental over-charging of any electrolytic capacitors.

5 SUMMARY

The PV power system for MIDNIGHT SUN incorporates several design features peculiar to a solar car. In choosing the batteries for the car, the battery mass was as important as its electrical efficiency. Therefore, the batteries selected would not be viable for stationary PV systems. The short life-time and high cost of the silver-zinc batteries are acceptable for use on a solar race car, but such batteries would be completely unacceptable for an electric commuter vehicle.

Multiple sub-arrays were used to compensate for the non-planar array shape. Maximum power tracking was used to good advantage in MIDNIGHT SUN, in part to allow summation of the power output from the four differently-irradiated sub-arrays, and in part to compensate for the large fluctuations in the voltage of the silver-zinc batteries used. For a stationary array, at most one MPT would normally be required.

Array orientation was not as important a consideration for MIDNIGHT SUN as it is for a stationary array since on a car the orientation will be constantly changing. Although some solar cars have tracking arrays, the decision was made to use a fixed, relatively horizontal, array on MIDNIGHT SUN based only on aerodynamic considerations.

The MIDNIGHT SUN project was perhaps less constrained by budget considerations than most PV power systems, but the race rules placed other constraints on the design process not normally encountered in PV system design. Different vehicle types and shapes will result from different sets of design constraints and criteria.

ACKNOWLEDGEMENTS

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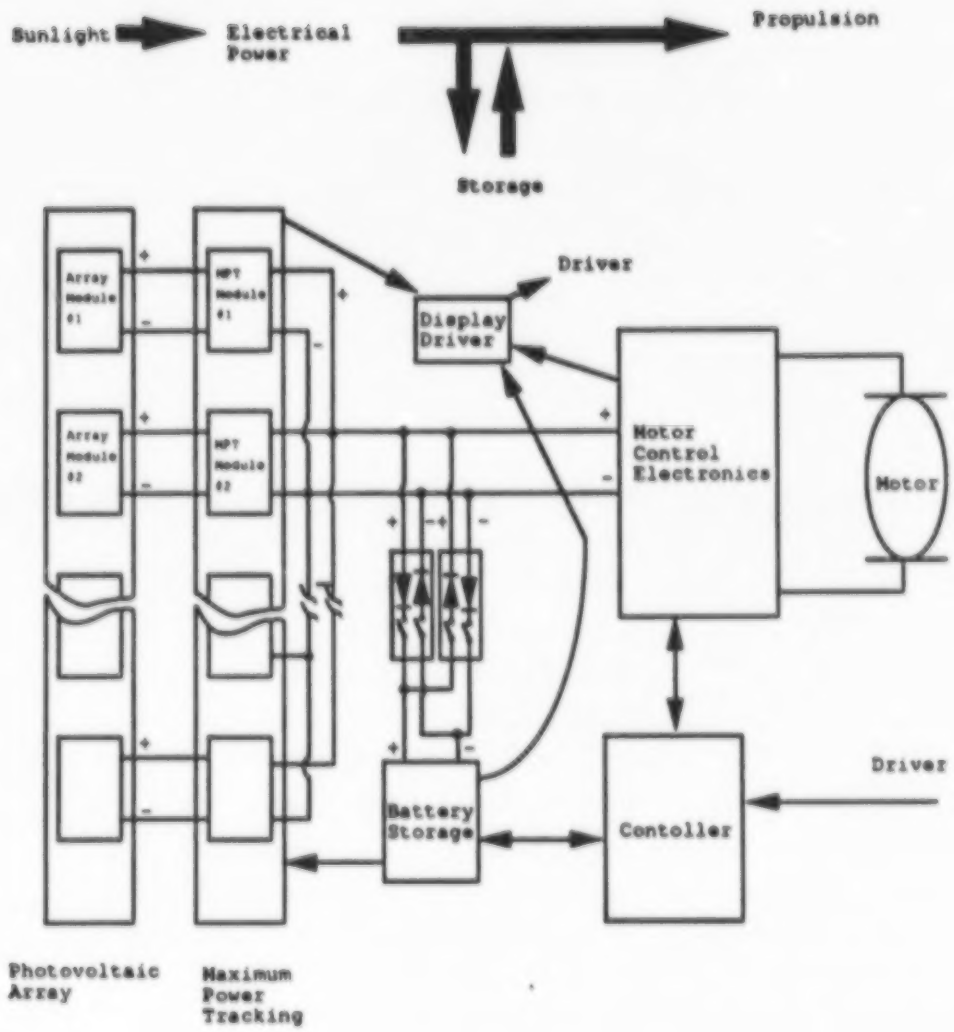

Figure 6: Overall Power System

Appendix D

List of Sponsors

The following organizations have given their generous support to the MIDNIGHT SUN project, which the authors and other team members acknowledge with thanks.

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